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ACCELERATOR BREEDING OF FISSILE MATERIAL

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The accelerator-driven breeder can extend an essential energy resource, fissile fuel for nuclear reactors, by a very large factor. Symbiotic breeders could be brought on line in a shorter period of time with favorable performance predictability. The economics of using accelerator breeding of fertile-to-fissile elements will become favorable as natural fissile material becomes scarce.

Without attempting to be at all complete in referencing the subject, the concept of converting fertile-to-fissile elements by use of charged particle beam generated neutrons dates back at least to the latter part of the 1940's. A classified paper of W. B. Lewis' in 1952 [1] develops almost all aspects of the approach in detail. In the early 1950's an attempt was made at the UC Radiation Laboratory to implement the concept with a linear accelerator, the MTA, Materials Testing Accelerator [2]. This project was cancelled after a fairly short and probably inadequate period of testing; it seems likely that the state of radio frequency power generation, high vacuum technology, ion sources, and the radiation damage data base were such that this effort could not have succeeded at that time in history. The broad interest in the early 1960's in high intensity particle beams and neutron sources led to numerous proposals for accelerators, generally falling into circular or linear machine categories. The persistence and perspicacity of Lewis must once more be brought to the fore in that his interest in the 1960's was to build a machine of 50 to 100 times the intensity of even the most ambitious of the proposals then extant, for instance, the Los Alamos Meson factory. The initial thinking at Chalk River was for a circular machine, but it took only one conversation on my part with Lewis to convert him to a linear accelerator concept, eventually called Intense Neutron Generator (ING), i.e., he was really the only one trying seriously to get a fertile-to-fissile fuel converter of the accelerator type. When the full-scale ING project was not supported nationally, a predominantly study-effort went on at Chalk River right up to the present, but elsewhere considerations of this kind came essentially to a standstill.

A brief reminder of the scientific rationale for considering the use of 1 to 2 GEV protons to make an intense neutron source follows. First of all, in this particular high energy region, protons are stopped primarily by nuclear collisions, having very long ranges to energy loss by electrons even in heavy targets such as uranium or thorium. Thus, nearly all the protons in the particle beam make nuclear collisions. In heavy nuclei the energy is dissipated by multiple intra-nuclear collisions, i.e., the so-called intra-nuclear cascade which then ejects numerous fast neutrons and protons. In addition to this source of neutrons, the heated compound (or residual) nucleus ejects a large number of slower neutrons essentially by evaporation in a spectrum peaking at a few MeV. For thick targets the integrated effect of these processes plus fast fission and including further production (multiplicati-) from the emitted primaries results in about 30 to 40 neutrons per proton which are available for further use. Adequately moderated, a major share of these neutrons will be captured in the fertile element until enough fissile material has been produced to use up neutrons in slow fission.

REASONS FOR RENEWED INTEREST

Several factors have contributed to the re-examination of the concept of electronuclear breeding. Not the least of these reasons is the realization that the reserves of uranium are likely to become a major bottleneck in the development of the nuclear power enterprise as now envisaged in the United States. This was particularly sharply pointed out by Silver [3] at the Impact of Geosciences on Critical Energy Resources Symposium of the AAAS in February 1978.

The major technological factors are present-day capabilities in very high vacuum technology and very high current ion sources both deriving from the fusion energy projects; high-power radio designs of accelerators carrying a hundred or a few hundred milliamps of proton current will be feasible both from space charge and beam spill aspects.

There is presently under design at LASL a prototypical injector and first 5 MeV of a 35 MeV deuteron accelerator which is intended to use the D-Li source to produce high intensities of fast neutrons for fusion program radiation damage experiments. This accelerator is planned to be sited at the Hanford Engineering Development Laboratory and to carry 100 to 300 MA beams. It is called Fusion Material Irradiation Test facility (FMIT). Although this accelerator is to produce particles of only 35 MeV energy, it is believed that the successful development of even the first 5 MeV portion of the machine will essentially guarantee the capability to go to 1 GEV or higher if desirable. Thus, the basic criteria for an accelerator useful for electronuclear breeding of nuclear fuels will have been met.

Another set of factors which have become important during the last several years to the nuclear energy enterprise are wholly or partially institutional in nature. The electronuclear breeder concept provides alternative technological fixes to some of these institutional barriers or impediments, encouraging a further re-examination of certain components of the whole ENB concept. The pressing institutional problems and perceptions pertinent to ENB are as follows:

1) The safety of fast breeder systems, especially liquid metal fast breeders.

2) The concern about the perceived human hazard of plutonium and no public indication that another fuel cycle can be considered. ^{233}U should have a much smaller biological hazard.

3) The incapability to respond acceptably to the public questions about long-term waste (or residuals) management.

4) The concern about terrorism, safeguards and the proliferation of nuclear weaponry.

How does the use of accelerator breeding affect these questions?

1) First is the recognition that electronuclear fuel producers could breed fuel for "acceptable" reactors such as LWR's without the intervention of a critical assembly and therefore an improved safety situation would result with respect to fast breeders.

2) It is in principle, possible to convert over entirely to a $^{232}Th/^{233}U$ power reactor system with no commitment to the use of ^{239}Pu at all.

3) The electronuclear breeding (ENB) concept is highly flexible technically and would allow tailoring production of fissile from fertile fuel in ways which could reduce the amount of high-level wastes over other methods. Furthermore, in addition to the neutrons the charged particle beam itself could be used to convert either the transuranic or fission product wastes into less objectionable elements.

These general points were made in a private communication to Dr. Richard Roberts in 1976, the then Assistant Administrator for Nuclear Energy in the United States Energy Research and Development Administration, following several years of futile attempts to interest almost anyone in ENB, beginning with a study of Carmichael and Vigil [4] at LASL in 1973. Following this initiative and the impacts of U.S. policies in the power reactor field, some small steps have been undertaken to address some of the critical issues as presently seen. The primary direction of these studies has been toward systems and assessments [5] although a very small effort has been devoted to experiments attempting to clarify some of the most sensitive portions of the data base. We will now discuss in more detail the technological and scientific situation. The many options possible in accelerator, target, coolant, etc., speak for the great flexibility of the method and has resulted in a wide spread in determinations of cost aspects for either power, fissile product or both. Only limited discussion of these options is possible.

THE CLASS OF LINEAR ACCELERATOR-DRIVEN HYBRID REACTOR SYSTEMS

This heading is used to distinguish between our subject matter and the parallel class of fusion/fission reactor hybrids which are presently under serious evaluation and which have many aspects in common.

As already recognized in the Carmichael/Vigil study of 1973, the three primary options for accelerator-driven systems are:

1) The fertile-to-fissile fuel producers--either with reprocessing or directly producing fuel elements for power reactors.

2) The fuel regenerator--in which conventional fuel elements of standard power reactors are reactivated nondestructively one or more times after being burned in light water reactors (LWR's) or heavy water reactors (HWR's).

3) The driven power reactor hybrid--added flexibility over the conventional reactor.

There appear to be no scientific or technological reasons why any one of these or various combinations cannot be made to work. The value of the individual options will depend on economics in <u>all</u> cases, on the status of the amount of the uranium resource available, now under intensive study in the National Uranium Resource Evaluation (NURE) program, pertinent to option 1; the status of isotopic separation capability, options 1 and 2; the status of fast breeder utilization, option 3; and whether spent reactor fuel is systematically reprocessed.

In the following figures the <u>last</u> of these three options is shown as a system schematic Figure 1 [3], and the obvious advantages are:

1) No enrichment is required.

2) Power can be drawn from a multiplicative but subcritical system.

3) Shutdown and safety control are very favorable.

4) The fuel resource is enhanced by several hundred times.

changed drastically.

2) Each reactor would need an accelerator adding a large capital cost.

3) Operational reliability of the accelerator must be at least as good as that of the reactor.

The accelerator-driven reactor concept will not be discussed in detail since at this time there is no strong proponent for this system.

THE LINEAR ACCELERATOR FUEL REGENERATOR (LAFR)

Staff of the Brookhaven National Laboratory (BNL) under H. Kouts and P. Grand [6], have made a detailed study of the accelerator-driven fuel regenerator, in their parlance, item 2 above. This is a very attractive option, particularly because it offers a method of stretching basic uranium resources which may be in serious jeopardy in the early decades of the 21st century. The favorable feature of doing the fuel regeneration without reprocessing, however, also contains a serious technological problem which must be answered experimentally, i.e., whether the fuel can tolerate the added swelling from the accelerator regeneration which produces large amounts of He compared to low-energy neutrons, and whether the clad can tolerate both the fuel swelling and its own radiation damage.

In Figure 2 is shown a BNL schematic design for a target to be used to regenerate pressurized water reactor (PWR) fuel assemblies. An elliptical proton beam impinges on a liquid metal Pb-Bi target formed as a jet-spray and perhaps as long as 10 meters. In this way the average target density can be reduced to a value compatible with a physically long neutron source necessary to provide a reasonably uniform neutron flux to the fuel element blanket. For this case there is no window between the beam-carrying target tube and the Pb-Bi target, thus requiring assurance that its vapor pressure does not have a chance to disperse the beam at any time. The fuel elements themselves have several options for coolants possible, e.g., liquid or two-phase D_2O, two-phase H_2O, or perhaps He.

The Pb-Bi target concept allows a flexible neutron source geometry which is useful for possible variations of fuel element dimensions and geometry, but a serious penalty is paid in neutrons/incident proton. The exact difference between Pb/Bi and Th or U is not well known at this time and is a matter which needs to be determined very soon.

Although the fuel regenerator concept is not restricted to the U-Pu cycle, this is the one espoused by the BNL group in a particular mode which begins with a partially enriched fuel, e.g., $\sim 2\%$ ^{235}U (this exposure is equivalent to $\sim$ 3000 MWD/T, i.e., 10% of total), uses the regenerator to breed in enough Pu to give a total of $\sim 3.2\%$ of fissile atoms, burns this fuel to $\sim$30,000 MWD/T and then nondestructively re-enriches the fuel once more in the LAFR so that another reactor cycle to a second 30,000 MWD/T can be accomplished.

The BNL conclusions are that in this way the fuel resource will have been extended decidedly, namely about 3.6 times, the enrichment plant requirement will be less by a factor of over 4, and spent fuel storage will be less by a factor of 2.

At the same time no reprocessing has taken place, and the fuel rods are at least as proliferation-resistant as in the conventional LWR once-through cycle; actually the in-reactor time is

With all the caveats and uncertainties of economic predictability, the above regenerator/reactor cycle would appear to produce electrical power at a total cost about 30% higher than if the present standard LWR cycle is used or about twice the full-cycle costs. This difference is small enough to encourage further detailed analysis of the approach and in particular to attempt to establish those parts of the data base which provide the most sensitive inputs to such evaluations.

THE ELECTRONUCLEAR FUEL PRODUCER (EFP)

This approach has been most seriously pursued by a group of scientists at the LASL, particularly Malenfant, Talbert, Russell, and Vigil [7]. In the following, emphasis will be given primarily to optimizing the use of the accelerator-breeder concpet for fuel production without taking into consideration present institutional/political impediments such as constraints on reprocessing, commitments to existing commercialized reactor systems, etc.

As a special case of accelerator implemented fuel production which is also a special case of fuel regeneration, a rough evaluation of a pure Th-^{233}U system will be considered in which the initial fuel production is itself carried out in already canned Th fuel elements intended for one or more reactor cycles before being placed in long-term fuel element storage without reprocessing.

A concept considered by the LASL group is a pebble bed integral target/blanket assembly as shown schematically in Figure 3. The coolant is sodium. The particular shape has the purpose of minimizing the back streaming of neutrons through the particle beam entrance. The advantages of the pebble bed approach are severalfold, e.g.:

Fuel loading and unloading are simple;

Fuel shuffling can be done on line;

Cooling design can optimize ratio of maximum to average heat deposition;

The spheres may be clad-metallic Th or unclad ThO;

Radiation damage is not very important;

The spheres may also be the fuel for an appropriate pebble bed power reactor.

Immediate evident disadvantages are:

The volume of coolant required;

The neutron leakage;

Pebble bed reactors are not in common usage;

If don't use pebble bed reactor, must reprocess.

Several models of this target/blanket design have been calculated with Figure 4 showing how ^{233}U is produced and removed as a function of the growth of ^{233}U. Table I shows more quantitatively the results obtained for the power generation in target/blanket for three values of ^{233}U:

POWER GENERATION SUMMARY

Total Power Generation, MW (Includes 630 MW in target from primary proton beam)	^{233}U Discharge 0%	2%	5%
Target	682	882	1404
Blanket	3	26	92
Total	6[illegible]5	908	1496
Target Peak-to-Average Power Ratio			
Axial	2.05	1.75	1.31
Radial	1.06	1.12	1.20
Combined	2.17	1.97	1.57
Blanket Peak-to-Average Power Ratio			
Axial	1.97	1.75	1.41
Radial	2.58	2.13	1.45
Combined	5.08	3.72	2.05

The annual production of ^{233}U is shown in Table II.

TABLE II

ANNUAL PRODUCTION OF ^{233}U

Average Concentration of ^{233}U in Target/Blanket	Discharge %		Zone
0%	0%	Target	539.2 kg
		Blanket	65.8 kg
		Total	605.0 kg
1.6%	2%	Target	539.9 kg
		Blanket	68.5 kg
		Total	608.4 kg
3.9%	5%	Target	548.8 kg
		Blanket	74.7 kg
		Total	623.5 kg

Note that approximately 600 kg of ^{233}U is produced per year in each case. To produce the power to drive the accelerator, about 600 MW(E) at 50% line-to-beam efficiency would require the burning of about 500 kg of ^{233}U if produced in an LWR. It is thus clear that the engineering design of the target/blanket should incorporate a power recovery system from the coolant which can be fed back into the grid or applied directly to the accelerator.

Not a unique issue for accelerator fuel breeding, but brought to the forefront rather sharply in this case, is the advantage of having the power production carried out by high conversion reactors as shown in Table III.

Conversion Ratio	Charge kg, ^{233}U	Discharge kg, ^{233}U	Annual Makeup Per 1000 MW(E) Reactor	Reactor Type
0.5	790	395	395	LWR
0.7	790	630	160	$^{233}U/ThO_2$ HTGR
0.9	790	710	80	$^{233}U/ThO_2$ PWR
0.97	790	766	24	$^{233}U/ThO_2$ Pebble Bed

When no one was concerned by the fact that the amount of oil available had a real and foreseeable limit, there was no great incentive for gasoline-efficient vehicles. Here, however, this same matter is apparent already in the fissile fuel economy, and the market place incentives for yellowcake production must be examined over a longer time period than is usually the case and as it should have been done for oil reserves.

ECONOMICS

We should now examine whether all, none, or some of the accelerator breeder options will hold up under economic evaluation. There seems to be little question that the technological problems can be solved, but it is necessary to look carefully at those technical parameters which may have high sensitivity to costs, i.e., which will determine whether we can afford the energy at the projected costs. It is just at this point that one notes that not only technological/engineering options and costs are not well enough known to narrow down the costs, but that even the scientific data base needs improvement before final design fixes can be made to optimize costs and efficiencies. This latter matter will be discussed below with respect to determining a course of experiments to be done which should narrow the range of uncertainty in some areas and probe regions of parameters where net gains may be expected.

There will be no attempt here to cover all of the economic studies and comparisons which have been made. In any case, the range of the costs is still very large, even when comparable scenarios and parameters are used, for instance, Kostoff [8] quotes a total range of estimated cost of accelerator bred fissile fuel in \$/gram lying between \$150 and \$600 with the majority between \$200 and \$350.

As a specific example of the complexity of the problem, the work of Flaim and Loose [9] will be discussed. In this study a comparison of traditional uranium fuel costs as used in the once-through LWR's is made with an accelerator fuel producer generating its own electricity. A further analysis is made of the present-value cost of electricity with and without fuel reprocessing for the uranium fuel cycle and for the electrically self-sustaining accelerator fuel producer. An example has been added to the Flaim/Loose study which takes into account (rather crudely) an option likely to be available for the EFP/LWR system and not for the conventional uranium fuel cycle, e.g., that fuel regeneration of two or more cycles without reprocessing can be accomplished allowing some portion of those costs to be dispensed with.

	Cost per gram of Fissile Element	At \$40/lb U_3O_8 Base Case	At \$200/lb U_3O_8	Regeneration Without Recycle
Traditional Uranium Fuel Cycle	\$40/gram of ^{235}U; diffusion plants	8.5 mils/kwh burning ^{235}U	11 mils/kwh burning ^{235}U	Not Applicable
Uranium Fuel Cycle with U and Pu Recycle	\$47/gram of ^{235}U; diffusion plants	8.3 mils/kwh burning ^{235}U	9.4 mils/kwh burning ^{235}U	Not Applicable
Accelerator Producer with Self-Sustaining Electricity	\$310/gram of ^{233}U	17 mils/kwh burning ^{233}U once	17 mils/kwh burning ^{233}U once	2 burns - 10 mils/kwh 3 burns - 8 mils/kwh 4 burns - 7 mils/kwh

Thus, the cost figures for electronuclear fuel production are quite unfavorable when taken in their simplest context. This is particularly apparent when one notes that the sensitivity to yellowcake cost is quite low even over a factor of 5. On the other hand, this factor of 5 or even 25 may not be so unrealistic as it seems in view of the widely differing evaluations of the magnitude of the reserves.

However, if one examines some of the technological options and scientific data base, the following are issues which are pertinent to the economics:

1) Can regeneration without chemical recycle be accomplished and how often?

2) Can one envisage a total nuclear energy enterprise that requires no isotope separation plant, even for the power reactors of the LWR variety?

3) What can one expect for eventual line-to-beam power efficiency?

4) What is an optimum fuel production efficiency?

5) How does the yield, angular distribution and spectrum of neutrons as a function of proton energy affect conversion efficiency?

CRITICAL ISSUES SUSCEPTIBLE TO PRESENT EXPERIMENTATION

The above issues are driven primarily by economic sensitivity. There are other questions which are of great technical importance but perhaps only secondarily economic. For instance:

1) What are the proton and neutron radiation damage effects induced in fuels, windows, etc.?

2) How much beam spill and activation can be tolerated?

thermohydraulically and nuclearly optimized?

5) Could the proton beam be used on transplutonium nuclides

   a) to enhance neutron yield?

   b) to study the disposition of transuranium (TRU) wastes?

6) In the Th-^{233}U fuel cycle one may expect reduced production of at least transplutonium wastes - what are the quantitative data involved and what is the impact on nuclear waste management?

Let us collect and discuss the critical issues pertaining to the accelerator first.

The large spread in cost figures for fissile material production by means of electronuclear conversion are a result, in part, of different data bases being used for such parameters as:

1) How much power can be recovered from the heat produced in the target/blanket?

2) What is the conversion ratio for line-power to in-beam power?

3) What is the number of neutrons per proton for various target materials and configurations?

4) What is the proton energy dependence of neutron yield?

5) What is the effect of neutron spectrum and angular distribution?

Although the cost per gram of fissile product is about a factor of six to eight higher than present costs, it is not inconceivable that better data on the nuclear yield parameters could allow optimization of the target/blanket configuration. Most calculations use 0.50 for the line-to-beam power conversion ratio; there is good reason to believe that the Russian Gyrocon tube can be developed to give considerably higher efficiencies, perhaps up to 80% which would begin to have a decided effect. A program of Gyrocon development is going on at the LASL by Tallerico and others [11] which may resolve the efficiency question reasonably satisfactorily.

A series of experiments have been planned for the LAMPF beam which should answer most of the crucial target/blanket nuclear physics questions. Some of these experiments are underway as a result of a collaborative effort with scientists from Canada. The work of Garvey, Fraser, Milton, Kiely, Pate and Thorson[10] at 350 MeV and 480 MeV is now being extended with their targets using the 800 MeV protons from the Los Alamos Meson Facility. Preliminary data on Pb and U indicate agreement between calculated and measured leakage neutrons from 10 cm diameter targets.

Table V shows an approach to an experimental program that will answer a considerable number of the critical questions in order of priority.

The experiments are listed in order of the proposed priorities, consistent with Weapon Neutron Research facility experimental area availability, early phenomenological indications, and reasonable demand on radiochemical foil analysis resources. Experiments involving uranium configurations could be exchanged with those for thorium, if desired by national program directives.

Experiment Number	Configuration	Techniques					
		Thermocouples	Fission Chamber	Foils - neutron spectrum	Foils - fission and spallation yields, conversion efficiencies	Time-of-flight	Foils/Immersion Tank - neutron production
1	Central core: Th	X		X		X	X
	U	X		X		X	X
	Al	X		X		X	X
2	Massive; homogeneous Th	X	X	X	X		
3	Massive; Al core, Th annulus	X	X	X	X		
4	Massive; Heterogeneous components selected on the basis of prior results	X	X	X	X		
5	Central core; Hetero-geneous, components selected on the basis of prior results	X		X		X	X
6	Massive; homogeneous U	X	X	X	X		
7	Massive; U core, Th annulus	X	X	X	X		

This series of experiments would require about two years to perform with an average personnel complement of about 6 full-time employees and a cost of about $1M. It should be noted that these experiments are still primarily integral experiments at a single energy 800 MeV using mostly thick targets (up to 26.7 cm radius) while the Ferficon experiments use small targets.

What other critical information is required for a truly quantitative assessment to be made for a series of design options?

above about 20 MeV are a necessity for a variety of fuel, cladding and window materials.

3) Experiments on the use of transuranic elements which are in large supply should be performed both with respect to neutron yields and with respect to the distribution of spallation and fission products for waste conversion purposes. Crude calculations indicate that the broad peak of the spallation residual nuclei lies about 26 mass units below ^{238}U + n, and that they extend down another 25 mass units lower.

4) The Th-^{233}U cycle should be studied with respect to the production of transuranic elements since it is likely that no plutonium isotopes and above will be produced. In fact, it is likely that only up to ^{235}U will be produced which will itself fission heavily.

5) The optimization of ^{232}U production should be examined either for maximum or minimum content depending on the ^{233}U utilization.

CONCLUSIONS

The most striking effect of the introduction of accelerator-driven hybrid reactor systems is the possibility of the total realization of Th and U reserves energy content. It is highly reassuring that this technology is mature enough that such a statement can be made. One is then primarily concerned with the questions of cost effectiveness. If one uses Kostoff's [8] estimated cost of fast breeder fissile fuel production costs, they are comparable to those of electronuclear breeding. The more favorable cost per gram picture he gives for magnetically and small pellet inertially-confined fusion is counterbalanced by the fact that scientific and technical feasibility has yet to be demonstrated. It is thus of great importance to carry out the truly inexpensive critical experiments for the electronuclear breeding concepts which, fortunately, the great flexibility of this concept allows.

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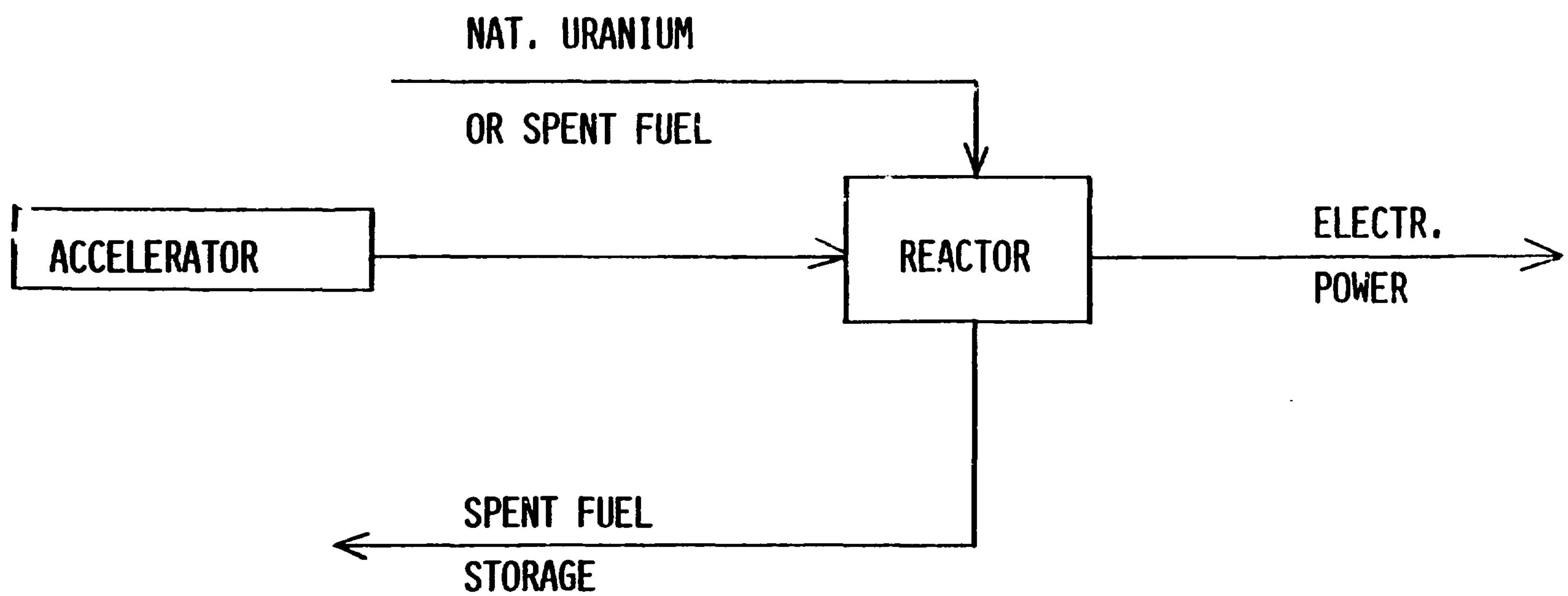
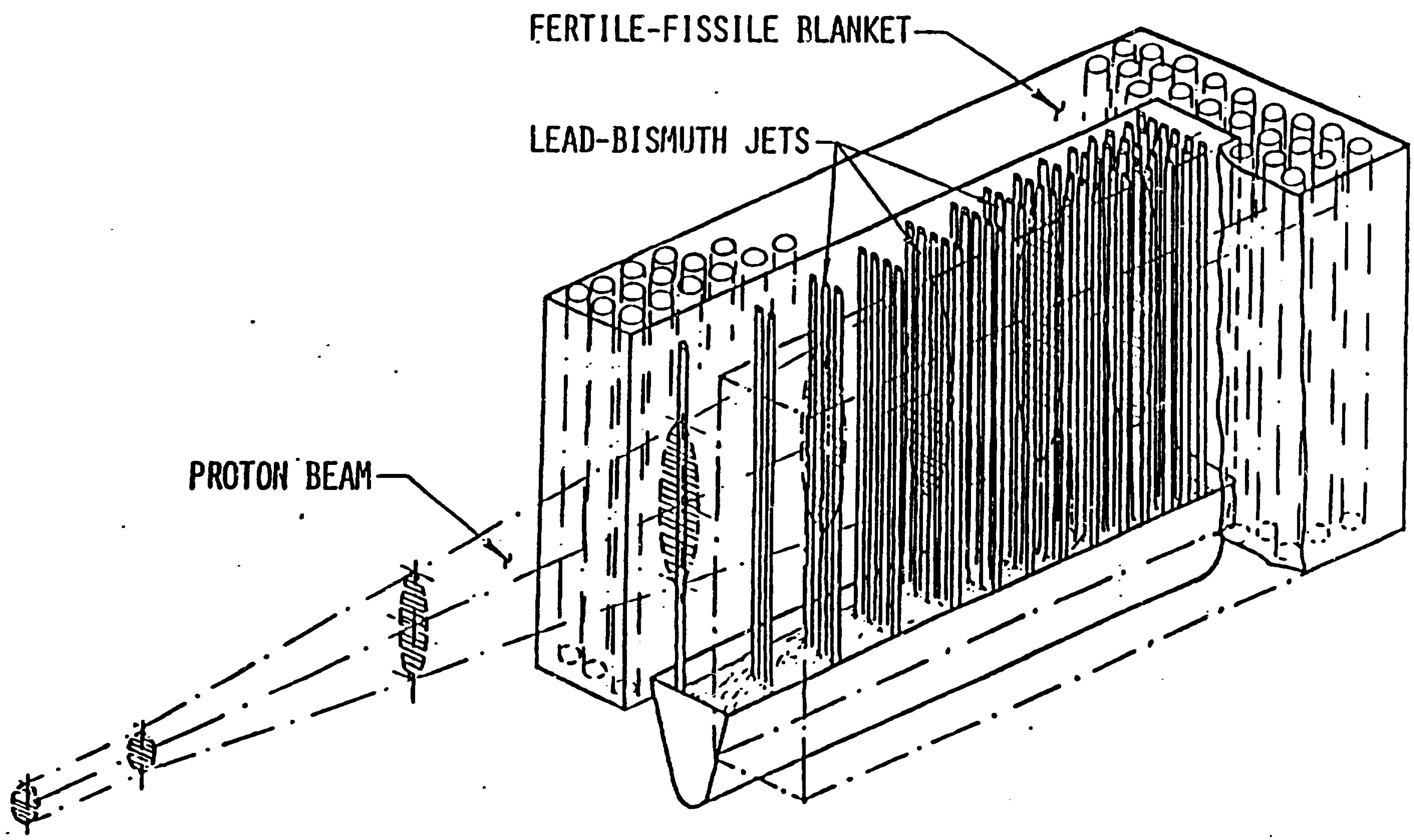


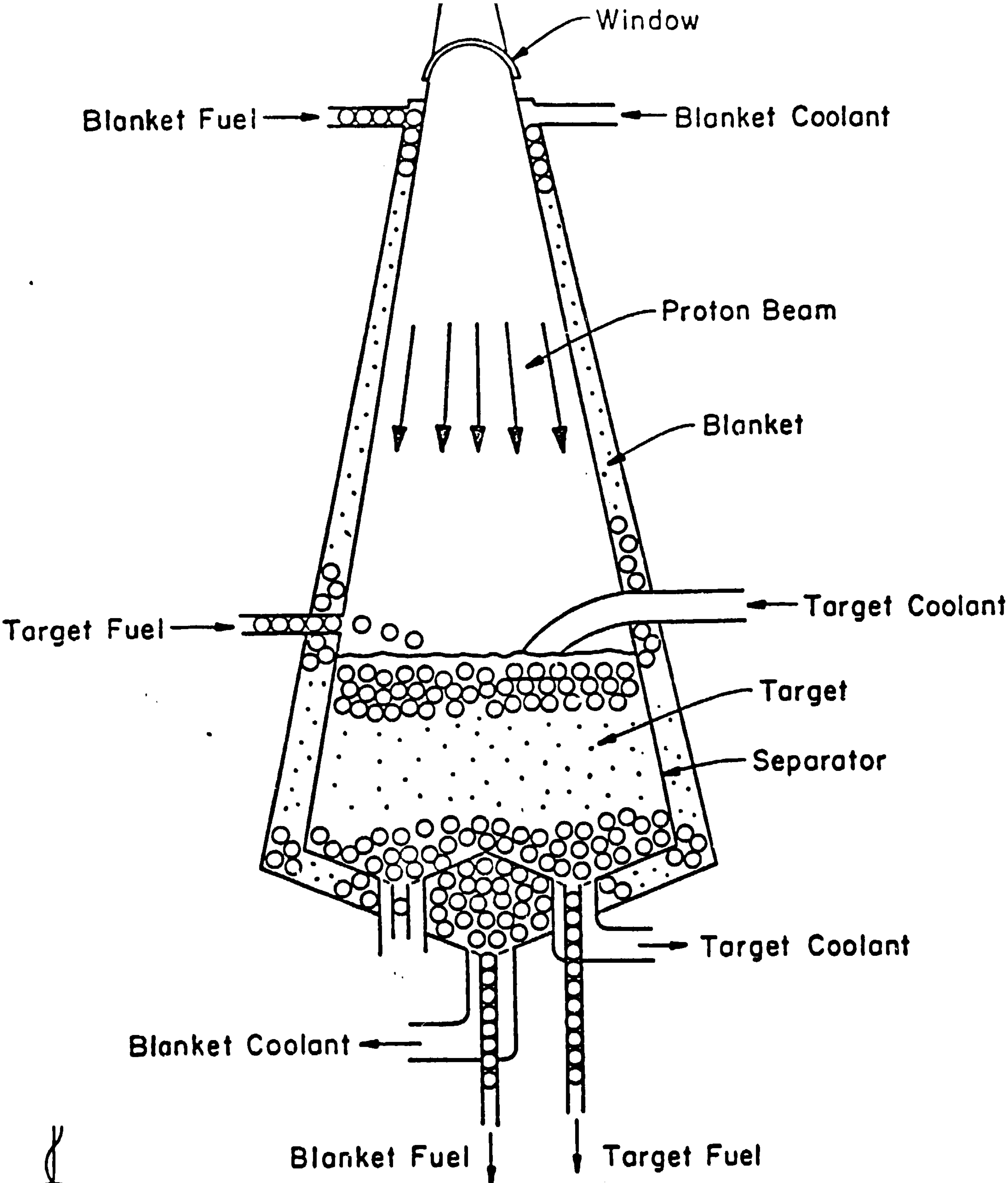
LINEAR ACCELERATOR DRIVEN REACTOR (LADR)

FIGURE 1.



SCHEMATIC TARGET FOR FUEL REGENERATOR

FIGURE 2.



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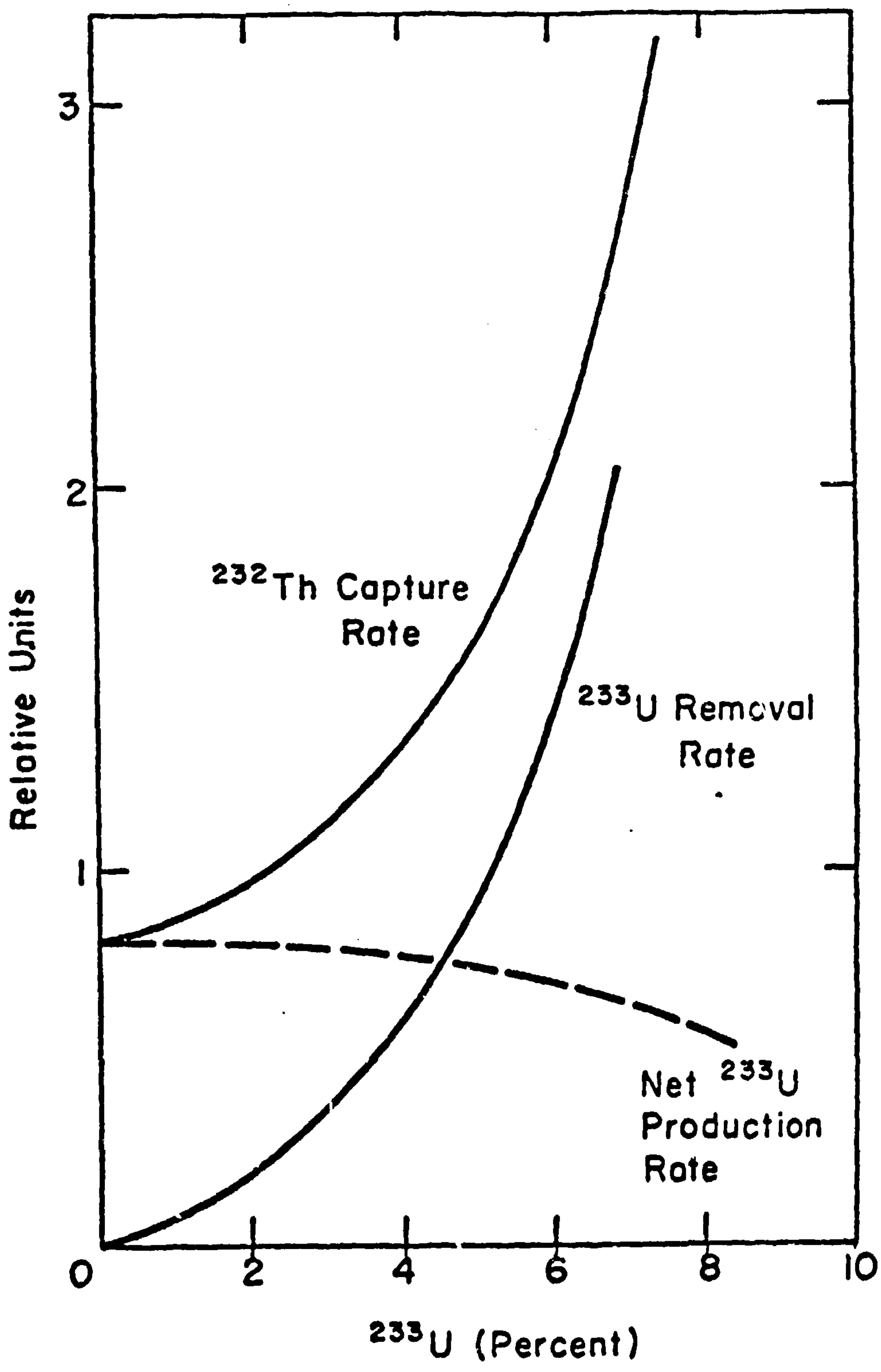
Pebble Bed Target-Blanket

FIGURE 3.



^{233}U Production And Removal Rates

FIGURE 4.